

# Operations Concept for the TES mission operations

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*Abstract* - This paper briefly outlines EOS Aura's Tropospheric Emission Spectrometer (TES) experiment and TES Instrument activities in operations. It describes the operations concept being developed for TES commanding, monitoring and analyzing TES health data..

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## 1. INTRODUCTION: TES INSTRUMENT AND EXPERIMENT DESCRIPTION

The TES Instrument, managed and built at the Jet Propulsion Laboratory (JPL), is one of four instruments on the Earth Observing System (EOS) Aura spacecraft. Aura is funded by NASA and managed and operated by the Goddard Space Flight Center (GSFC). The spacecraft is being developed at TRW, and is scheduled for launch from Vandenberg Air Force Base in June, 2003. EOS Aura will study atmospheric chemistry from a 705-km

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altitude, 98.2° inclination sun-synchronous polar orbit with a 1:45 pm local solar time equator crossing. The other three instruments on Aura are the High Resolution Dynamics Limb Sounder (HiRDLS), the Microwave Limb Sounder (MLS) and the Ozone Monitoring Instrument (OMI). Once in orbit, Aura is designed to operate for at least five years.

The Tropospheric Emission Spectrometer (TES) is an infrared imaging Fourier transform spectrometer (FTS) which will measure and profile virtually all infrared-active molecules in the Earth's lower atmosphere. It has a spectral range of 3.3  $\mu\text{m}$  to 15.4  $\mu\text{m}$ , and a resolution of 0.025  $\text{cm}^{-1}$ . It operates using both natural thermal emission (4.1 to 15.4  $\mu\text{m}$ ) and solar reflection (3.3 to 5.0  $\mu\text{m}$ ).

The focus of TES is on the global distribution of tropospheric ozone and on the factors that control its concentration, in order to support development and improvement of models of the present and future states of

the Earth's lower atmosphere. Accordingly, TES will generate vertical concentration profiles of ozone, methane, water vapor, nitric oxide, nitrogen dioxide, and nitric acid from the surface to the lower stratosphere. It is to provide these measurements for roughly 18 orbits out of every 29, to the extent possible given cloud interference and other physical limitations. In addition, it will determine local atmospheric temperature profiles and surface temperatures, and measure a large variety of other chemical species that are of sporadic or specialized interest, such as those produced by volcanoes, biomass burning, or industrial accidents. When over land, it will also measure emissivities and reflectances where possible.

TES obtains its data in observations of 4-second duration in the nadir direction and 16-second observations while staring at the trailing limb. The nadir observations supply limited vertical resolution but excellent horizontal spatial resolution, while the limb observations provide good vertical resolution and enhanced sensitivity for trace constituents at the expense of having poorer line-of-sight spatial resolution and a higher chance of cloud interference.

TES produces up over 350 gigabits (Gb) of raw interferogram data every two days. As Figure 1 indicates, these data, along with instrument engineering data and other ancillary data, are transmitted back to Earth in spacecraft contact sessions of several minutes apiece, once per orbit, via a 155 Mbps X-band link. The data arrive at ground stations in Alaska and Norway and are then transmitted electronically to the EOS Data and Operations System (EDOS) at GSFC in telemetry packets. These data are then sent to the Distributed Active Archive Center (DAAC) at the Langley Research Center (LaRC) where they constitute Level 0 data sets and then to JPL for processing by the TES Science Investigator-led Processing System (SIPS).

These Level 0 data sets are then sent to JPL for processing by the TES Scientific Investigator-led Processing System (SIPS). The initial SIPS processing, called Level 1A, converts the serial bit stream from the spacecraft back into interferograms, which are essentially the initial output of the instrument. The Level 0 bit stream is of 16-bit integer "Data Numbers" (DN) values and the Level 1A 32-bit floating point outputs are reversible back to these DN values. Also included in Level 1A processing are important ancillary data such as time, date, spacecraft and target location, and instrument pointing.

The next processing phase is Level 1B, in which the interferograms are converted, through phase correction, Fourier transformation, and calibration to radiometrically calibrated spectra, corrected for off-axis instrument line-shape distortion, and resampled onto a common frequency grid. While this phase is computationally intensive, its load is only about 10% of the load for Level

2 processing. Before the Level 1B data is passed to Level 2, data quality flags are added to the header.

In Level 2, the spectra are converted into vertical volume mixing ratios of the selected molecules. These ratios and temperatures are placed on a pre-determined pressure grid (not an altitude grid). This process is called "retrieval." While the volumes of the retrieved profiles are themselves very small, there is a final step in which a complete spectrum based on the retrieved profiles is computed and subtracted from the observed Level 1 spectra. This produces a file of "residuals" which is as big as the output of Level 1A or Level 1B. The profiles and residuals constitute the primary data product of TES. Accompanying the profiles are complete error covariance matrices to provide an objective estimate of the quality of the retrievals.

Level 2 processing for data taken during 16 orbits of Global Survey is performed at the SIPS. Data taken for special research observations of volcanoes and other specific targets, taken during the gap between Global Surveys, are sent to the TES Science Computing Facility (SCF) for Level 2 processing.

In Level 3, the Level 2 profiles are interpolated in three dimensions to generate a series of global and regional concentration maps, one set for each chemical species. This processing is performed at the SIPS. Non-routine analyses of special products (non-Global Survey) are classified as Level 4. The Level 3 products are anticipated to be the most commonly used TES browse product, although more serious users will probably request the Level 2 profiles as well. All these products will be in the public domain and be available from the NASA LaRC DAAC archives at the cost of reproduction.

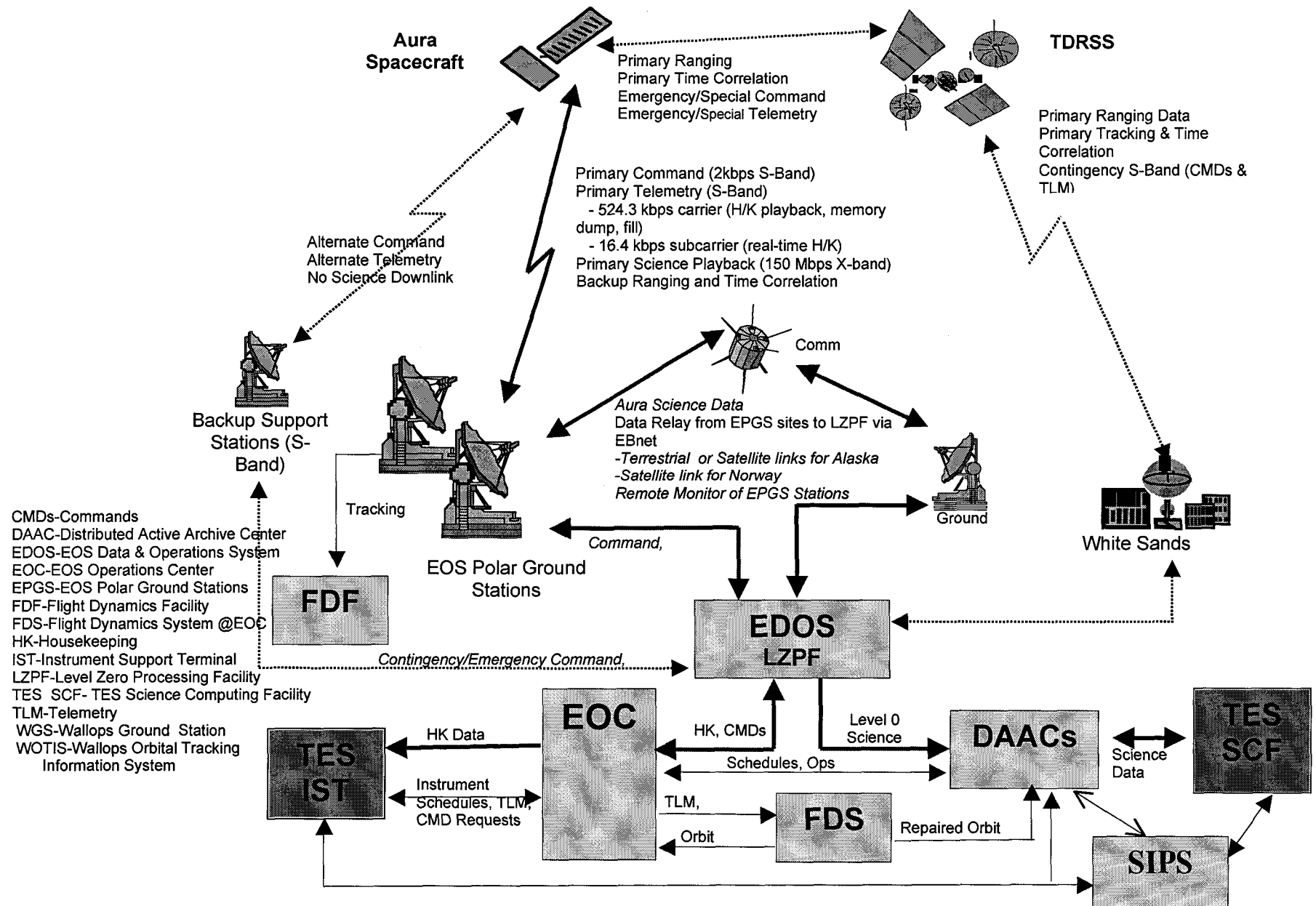


Figure 1. TES Mission Operations Architecture

## 2. TES Mission Operations

TES instrument will operate continuously. The nominal-operating sub-mode for the TES instrument will be Mission. Changing sub-modes will be infrequent. Instrument activities will be pre-planned and scheduled. TES flight computer commands necessary to carry out the mission objectives will reside in macros. These macros will be triggered for execution from the ground. The commands to trigger the macros for execution will be loaded during the Aura TDRS (Tracking Data Relay Satellite) contact periods or the Polar Ground Station contact periods. Special observations will change according to the nature of the study. The instrument commands are loaded by the FOT at the EOC during Polar Ground Station contact periods.

## 3. TES Macros

Macros are a set of commands stored onboard TES. Each macro generally consists of 5 to 30 commands. These commands have relative times and are stored onboard TES. The macros use a table to obtain some command parameters. The macros operate serially and no more than one macro can operate at one time. If a command is issued to halt a macro the commands in the macro already issued will continue to operate and the new commands in the macro waiting to be executed will be inhibited. Once a macro is halted it may not be resumed. A macro may be activated by another macro. A macro may contain nested loops. The maximum number of words in a macro is 256. Commands spacing within a macro must be less or equal to 6554 seconds as an orbit duration is 5933 seconds. The maximum number of macros that can be stored onboard TES is 512. Each macro has a unique ID.

### Global Survey Macro

Global survey macro will generate the main TES standard product science activity. A TES global survey macro will consist of seven scans: one 4 second-view of cold space, one 4-second view of the RCS, two 4-second nadir views, and three limb views of 16 seconds each. The total duration of a global survey macro is 81.2 seconds. The global survey macros will be triggered using the orbital event South Pole Apex crossing.

### Non Global Survey Macros

Non global survey macros will require most of the planning and scheduling by the TES IOT although they generate about one percent of data of TES. Thenon global survey macros consist primarily of calibration macros and special observation macros. Most of these macros will either be triggered using the South Pole Apex crossing as an orbital event or a target as an orbital event. The targets can be either the targets that reside

onboard TES or could be targets of opportunity which are targets that are unplanned.

### *Calibration Macros*

Calibration macros are of three principle types: radiometric, spatial, and spectral.

Radiometric calibrations are performed as part of the Global Survey macros, and are also included to bracket special science observations. The purpose is to obtain a calibration accuracy of 1% or better, so that line-of-sight temperature profiles will be known to 2 K or better. This temperature resolution is needed to avoid compromising abundance retrievals. The radiometric calibration macros also include tests at different radiometric source temperature, using every filter. These "linearity" calibrations should each take about 11 orbits to perform, because the radiometric source must be allowed to cool down to each of the required source temperatures. It is estimated that there will be two such calibrations per year. There are also two "gain" calibrations per year, to determine the relative gains within each gain-switchable signal chain, again requiring different radiometric source temperatures. In addition, there will be occasional long-scan calibrations, to verify that the short-scan calibrations are sufficiently accurate for long-scan calibrations.

Spatial calibrations are needed because TES uses four independent but optically conjugated detector arrays. To register the data from each detector, the relative pixel positions must be known to 1% or better in both directions. In addition, pixel-to-pixel sensitivity variations need to be known to at least 0.5% or better to facilitate the radiometric calibrations.

Spectral calibrations will be performed in ground testing, using both monochromatic sources and gas cells. However, during flight, spectral changes will be monitored from the atmospheric spectra themselves, so no flight spectral calibration macros are needed.

### *Special Observation Macros*

There are at least ten volcanoes that TES will want to monitor on a regular basis (this list will change with time). They are Colima (Mexico), Erebus (Antarctica), Etna (Sicily), Fuego (Guatemala), Kilauea (Hawaii), Lascar (Chile), Masaya (Nicaragua), Pacaya (Guatemala), Sakurajima (Japan) and White Island (New Zealand). The plan is to observe each of these volcanoes, repeat each observation 2, 16, and 18 days later, and revisit each site twice more during the year, with the same observing pattern. Each observation will consist of

212 seconds of data taking, bracketed by 312-second pre- and post-calibrations, for a total of 836 seconds. [2]

There will also be observations of various industrial catastrophes, with observations repeated 2, 16, and 18 days later.

An Urban/Regional Pollution campaign will involve an estimated 10 events per year, with observations repeated 2 days later. A Regional Biomass Burning campaign will involve an estimated 2 events per year, with observations repeated 2 days later. There will also be a campaign to observe stratospheric effects of volcanic eruptions. One event per year is estimated.

TES also plans to perform two intercomparisons with Aura's HiRDLS instrument per year. TES would make limb observations of the same places as HiRDLS at the same times in an attempt to improve both data sets. Each intercomparison is planned for a little less than one orbit.

#### *Fault Protection Macros*

Fault protection macros are macros that are needed onboard to facilitate autonomous fault responses to anomalous instrument behavior as well as to permit pre-emption of such responses by ground triggering. The standard ground response to an anomaly is to halt any active macro and put all mechanisms in neutral positions; this is the purpose of the "Safe" macro. If there is an Aura spacecraft problem that requires TES to be shut down, the "Shutdown" macro will be used. In addition, there are macros to handle any given subsystem specifically. These include the pointing control subsystem, the interferometer control subsystem, the filter wheel heaters, the focal plane coolers, and the calibration sources.

#### *Activation Macros*

Most of TES activation will be accomplished using real-time commands, however some of the TES activation steps that will require several hours will be accomplished by triggering a macro onboard TES from the ground. These macros will also be used in pre-flight testing, and some of which may be kept on board for potential use in flight as well.

Macro Name	# of Commands	# of Words	Macro Duration	Comments
<b>Global Survey</b>				
TES SUPER GS	10	35	4 orbits	One segment of a 16-orbit Survey
TES GS SUR	29	85	81.2 sec	81.2 Second Global Survey
TES GS CAL	28	80	1 orbit	Global Survey Pre-Calibration
TES SUPER CAL	10	36	2 orbits	Calls TES GS CAL
TES GS RESET	5	17	15 seconds	Resets PCS and ICS after Global Survey
TES GS QLSUR	31	89	81.2 sec	Includes one scan of expedited data

<b>Non Global Survey</b>				
<i>Special observation</i>				
TES VOLCANO	11	40	836 sec	Stare with 4 filter set (Quad stare)
TES BIOMASS	11	40	542 sec	1 fixed filter per lat/lon step
TES REGPOL	11	40	976 sec	3 fixed filters per lat/lon step
TES INDCAT	11	40	1044 sec	Quad stare w/4 fixed filters at 1 lat/lon
TES STRAT	11	40	542 sec	Long Scan transect
TES HIRDLs	22	77	4874 sec	Target 32 km above limb
TES STARE1	12	42	430 sec	One target, One filter, short scan
TES STARE2	12	42	638 sec	One target, two filters, short scan
TES STARE3	12	42	846 sec	One target, three filters, short scan
TES TRANS2	11	40	762 sec	Two fixed filters per lat/lon step
TES TRANS4	11	40	1179 sec	Four fixed filters per lat/lon step
TES VOL MEAS	12	40	212 sec	Quad stare
TES BIO MEAS	10	36	334 sec	Single transect
TES POL MEAS	12	40	152 sec	Triple transect
TES STR MEAS	11	38	334 sec	
TES TH MEAS	13	42	1104 sec	
TES STARE1 MEAS	9	18	222 sec	
TES STARE2 MEAS	12	22	222 sec	
TES STARE3 MEAS	12	22	222 sec	
TES TR2 MEAS	12	40	346 sec	
TES TR4 MEAS	12	40	347 sec	
<i>Calibration Macros</i>				
TES GAIN CAL	23	84	400 mins	
TES AP CAL	14	39	52 sec	All-purpose short-scan calibration
TES APL CAL	13	19	38 sec	All-purpose long scan calibration
TES BK1 CAL	5	22	104 sec	1-filter calibration
TES BK2 CAL	7	26	208 sec	2-filter calibration
TES BK3 CAL	7	26	312 sec	3-filter calibration
TES BK4 CAL	7	26	416 sec	4-filter calibration
TES BK5 CAL	7	26	520 sec	5-filter (full filter) calibration
TES HILO CAL	13	39	1200 sec	
TES LINEARITY CAL	16	46	800 mins	One orbit for each temperature
TES SPATIAL CAL	10	30	1144 sec	
<i>Fault Protection</i>				
TES SHUTDOWN	43	144	134 sec	Critical macro shuts down TES
TES SAFE	8	22	37 sec	Puts mechanisms in Safe state
TES PCS OFF				Opens PCS 28V power relay
TES PCS SAFE				Puts PCS in safe state
TES ICS OFF				ICS shutdown
TES FPHTRS OFF				Powers down FP motor heaters
TES FPHTRS ON				Heats FP motors
TES FPCA OFF				Powers down FPC A
TES FPCB OFF				Powers down FPC B
TES CALSRCE OFF				Opens Cal source 28 V relay
<i>Activation Macros</i>				

#### 4. TES Uplink Operations

TES Uplink Operations will consist of planning and scheduling activities.

The TES instrument will operate in two-day increments (1 day of special activities followed by 1 day of Global Survey). TES uplink operations will generate and schedule the eight days worth of sequence requests at one time. Late updates to “tweak” timing of special observations may be required. The TES macros will reside on-board, so TES IOT will trigger these macros using the planning and scheduling process software.

##### Planning and Scheduling

The TES Project scientist and Investigator Working Group will produce a longer science plan for the Aura mission. From this work, TES PI (Principal Investigator) will produce a longer term instrument plan which will define the goals and objectives for the instrument TES. Once in orbit the initial schedule phase will begin four to five weeks prior to the target 8-day week to allow the EOC FOT to generate TES instrument resources. The TES activities will be defined in a timeline. This schedule will form the basis for commanding. Special activities will require last minute timing updates and will be submitted seven hours prior to uplink.

The TES Instrument Operations Team (IOT) will request the planning products necessary to plan TES mission operations. The TES IOT will schedule the TES activities and perform constraint checks to ensure that no constraint violations that have occurred. Once these activities are scheduled the Flight Operations Team (FOT) at Goddard Space Flight Center (GSFC) will maintain the accuracy of the activity execution times by updating the predicted times of orbital events.

The TES IOT will request expedited data service for activities that occur for the first time in orbit for analysis purposes by scheduling activities that issue commands to the instrument to set the “expedited” flag in the TES data. The activities set and reset the flags of the packets with the desired application process identifiers (APIDs). In addition, the TES IOT may use the capability of requesting all data from a realtime event to have expedited data processing. In this case, the TES IOT provides the request to the FOT. The FOT is responsible for coordinating with personnel to obtain the requested data processing.

#### 5. TES Realtime operations

Real-time operations will consist of spacecraft/instrument command uploads, command verifications, and capture of spacecraft/instrument telemetry (both real-time and stored

data). The telemetry will be downlinked every orbit. These operations are the responsibility of the IOT and FOT at GSFC.

The need for TES real-time command operations will be minimal during the nominal mission, however, there will be periods where TES will require significantly more real-time commanding. This will occur during the instrument checkout phase (specifically for initial instrument turn-on, cooler turn-on, earth shade unlatch and decontamination). Real-time commanding and monitoring will also be required when loading flight software or macros (for memory dumps). TES emergency/contingency operations will also require real-time command support, as needed. This includes instrument safing (if the instrument or spacecraft has not already safed TES), and any recovery scenario to return the instrument back to its nominal operating sub-mode.

The activation period is from Aura Launch date to 90 days after launch during which time the TES commanding will be intensive. During this period the TES IOT will monitor the data 24 hours a day. Once TES reaches nominal operations TES will be a pre-planned mission with limited real time commanding. The IOT will not support routine real time operations. During special planned instrument operations and all unplanned real-time commanding during TES anomalies, the IOT will support the FOT by monitoring the operations via the Instrument Support Toolkit (IST). The IST is the IOT’s window into the operations center at GSFC for Aura.

TES realtime operations functions will be performed immediately before, during and immediately after a scheduled contact with the Aura spacecraft. Pass plans which contain contacts with Tracking Data Relay Satellite (TDRSS) and Polar Ground Stations and command procedures that contain TES commands to be sent to TES in realtime during these realtime contacts are the primary products used during TES realtime operations. The FOT at GSFC will use these pass plans as a guide and send memory loads, TES realtime commands with TES IOT approval. The FOT notifies the IOT in the event a spacecraft or contingency affects the planned commanding.

The IOT will submit realtime command requests to the FOT at any time. In an emergency situation, these requests will be acted upon by the FOT at the first available opportunity. In non emergency situations, these requests are usually submitted about 30 minutes before the real time contact.

In order to prepare the FOT to perform telemetry monitoring, the IOT will train the FOT personnel on the proper operation and monitoring of TES.

Monitoring TES health and safety will be performed using telemetry displays with red and yellow alarm checks on selected telemetry (low rate engineering). Primarily the checks will be made on subsystem temperatures, voltages and currents. TES operations will also monitor the eight passive analog channels provided in the spacecraft housekeeping data. It is currently assumed TES IOT will use Epoch 2000 (provided by GSFC) for this analysis.

Monitoring the spacecraft/instrument health and safety from the housekeeping telemetry will also be considered a real-time task. The TES IOT will monitor the health and safety of the instrument through the IST during the 5-day prime shift workweek. The FOT at the EOC, GSFC shall perform the monitoring task 24 hours a day, seven days a week.

## 6. TES Housekeeping Data Analysis

The TES Instrument Operations Team (IOT) will analyze the instrument housekeeping and engineering data to verify the performance of the instrument. The IOT will also be involved in long-term trending of performance and tracking the use of limited life items. The TES IOT will inform the Flight Ops Team (FOT) of any instrument performance changes or trends that indicate degraded current or future performance. The TES IOT will provide periodic reports on the status and performance of the instrument. The IOT will assist the FOT with investigation of performance anomalies requiring TES instrument expertise.

When the TES IOT identifies an anomaly, the FOT will assist with the investigation, including requesting additional or extended telemetry contacts, executing unplanned procedures, uplinking unplanned commands and memory loads, and performing special data analyses.

## 7. TES Launch and Activation

Prior to launch, the Aura community will generate an Integrated Mission Timeline (IMT) based on the inputs provided by the IOTs. This timeline will define a baseline of events for the launch and activation phase of the mission.

The IMT will reflect the events to be accomplished via realtime commanding using command procedures developed in CECIL or using stored commanding. Before launch, the FOT will use the IMT to generate the first few days of pass plans for contact with the TDRSS satellite or Polar Ground Stations.

TES IOT will be responsible for providing staff at the GSFC EOS Operations Center (EOC) to support launch

and activation activities defined in the IMT. This will involve 24-hour support for the first week following launch. The subsequent days required to complete instrument activation are up to 12 hours per day, 7 days per week.

TES instrument operations teams duties during this time period will be participating in daily briefing meetings, providing periodic instrument status, participating in command authorization meetings, providing verbal authorization to proceed through TES instrument command procedures, participating in scheduling activities, review of the daily scheduled activities, reviewing of telemetry during each contact with the Aura, analysis of back orbit data, assistance with evaluating any Aura anomalies, and validation of the ability to transition operations to their remote facility.

## 8. Anomaly Operations and Contingency Planning

The IOT will define TES telemetry data, the operational limits, and the reaction for each out-of-limit condition. These reactions are command procedures and will be developed using the online system. During each spacecraft contact, the FOT will evaluate all out of limits conditions, and take appropriate actions, when necessary, as defined by the IOT.

In the event of an anomaly, the FOT will most likely be the first to identify the irregularity. When health and safety violations (i.e., red limits) conditions occur, FOT will first take actions appropriate to preserve the instrument and spacecraft safety. The IOT has primary responsibility for the investigation and resolution of instrument anomalies. The FOT will assist the IOT with instrument anomaly investigations when requested. The FOT has the primary responsibility for investigation and resolution of spacecraft anomalies with support from the entire Aura operations community. IOT and ground system personnel assist in resolving anomalies when requested. FOT actions will include actions such as initiating TES contingency procedures, notifying the TES IOT on call engineer to coordinate actions, which relate to instrument operations.

## 9. TES Mission Operations Tools

The main tool to perform TES mission operations will be the Instrument Support Toolkit (IST). The IST will consist of two sun workstations and two NTs. The NTs will be used to monitor the TES instrument health and safety data in realtime. The NTs will also be used to do develop realtime command procedures that will be used during TES activation period and nominal operations and contingency purposes. The sunworkstations will be used



for planning and scheduling of the macros for Global and non global survey observations. The sunworkstations will also be used to analyze the TES housekeeping data.

## 10. TES mission operations plan

### *TES Instrument Operations Team (IOT)*

The TES IOT will consist of two members.

The TES IOT will work a 5 day, 8 hour week, except for the first ninety days after TES launch or during special activities. The TES IOT will reside at the EOS Operations Center (EOC) for the initial activation during the first ninety days. During the lifetime of TES, the IOT will be on call at all times. The instrument will be operated through the use of the Baseline Activity Profile (BAP) for the super global survey macro execution. IOT will overlay special observations as necessary. The BAPs and activities will be planned and scheduled using the planning and scheduling application of the IST. TES will be monitored during the initial activation and to do routine monitoring on a daily basis at every R/T contact everyday, 24 hours a day. IOT will develop contingency procedures, limits and responses for the Flight Ops Team (FOT) to use in the monitoring of the instrument, and provide contacts for anomaly responses

### *A Day in the life of TES mission ops prelaunch*

IOT will develop and test Activities that will be used to trigger the macros onboard TES using the Planning and Scheduling application of the IST. IOT will develop and test constraints using flight rules document and the constraint builder application of the IST. IOT will develop Real Time command procedures to command TES during activation and during TES operations using the online system of the IST. IOT will test Real Time command procedures using the spacecraft simulator at the EOC, GSFC. IOT will prepare operational procedures (how to's) IOT will prepare documents such as mission operations plan, Flight Rules, etc.. IOT will define red and yellow limit responses for anomaly resolutions. TES IOT will validate Project Database in the EOC, Ground system that contains TES commands, telemetry etc. TES IOT will support Integration and Test (I&T) at TRW. TES IOT will support Launch/mission rehearsals/simulations/training and any meetings in preparation for launch

### *A Day in the life of TES mission ops post launch*

Planning and Scheduling  
Real Time commanding/monitoring  
Analysis  
Writing status reports and support the Science Data  
Processing segment  
Always on call

## 11. Conclusions

This paper has described the TES Instrument Operations Concept and operations tools to be used in TES Instrument Operations. The most involved tasks are the TES activation period, changes to be made to TES macros onboard TES post launch. However, in nominal operations a great deal of planning and scheduling and analysis is required.

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